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NUCLEAR-ACTIVE HIGH ENERGY PARTICLES AND THE ACCOMPANYING EXTENSIVE COSMIC RAY SHOWERS

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NUCLEAR-ACTIVE HIGH ENERGY PARTICLES AND THE ATTENDING EXTENSIVE COSMIC RAY SHOWERS *

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SUMMARY

Experimental results are given on the energy spectrum of nuclear-active particles in the region $3 \cdot 10^{12} - 10^{14}$ eV at the 3860 meter altitude above sea level, alongside with data on extensive air showers accompanying them. The energy spectrum cannot be described by a power function with a single exponent in the entire region considered. The mean free paths for absorption and interaction of nucleons in the atmosphere are determined. For particle energies above 10^{13} eV they are equal to 120 g/cm^2 and 83 g/cm^2 respectively. An analysis of the distribution of extensive air showers, accompanying nuclear-active particles with energies $\gg 3 \cdot 10^{12}$ eV with respect to the total number of particles indicates that the character of the elementary interaction act changes for nucleons with energies higher than 10^{13} eV.

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Investigations of extensive air showers of cosmic radiation have shown [1], that their utilization for the study of collision processes of particles with energy $> 10^{13}$ eV requires inescapably detailed measurements of the structure and composition of the air-shower core.

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* YADERNO AKTIVNYYE CHASTITSY VYSOKOY ENERGII IS SOPROVOZHDAYUSHCHIYE IKH SHIROKIYE ATMOSFERNYYE LIVNI KOSMICHESKOGO IZLUCHENIYA

On the other hand, observations of nuclear-active particles with energy $> 10^{13}$ eV in the atmosphere depth with the aid of ionization chambers are linked in an overwhelming number of cases with the simultaneous registration of air showers, attending these particles. Therefore, two different approaches to the study of processes at high energies have been reduced to a single experiment setup.

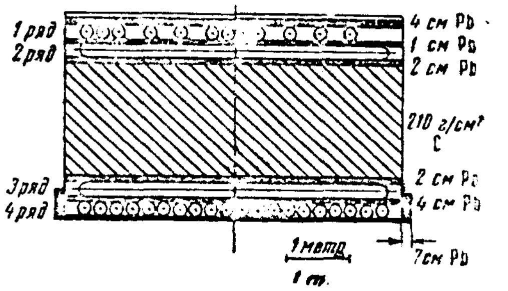

Fig. 1. - Detector of nuclear-active particles and electron photon avalanches of high energy

Discussed in our paper are the results of such type measurements, completed at the altitude of 3860 meters above the sea level. Two series of ionization chambers, placed under a thick carbon layer inside the cavity formed by the lead, shielding it, are schematically indicated in the installation of Fig. 1. These chambers were designed for the registration of high-energy nuclear-active particles. Two more series of ionization chambers were disposed above the carbon under a relatively thin layer of lead for the measurement of the electron-photon component of the air-shower core. Hodoscopic counters were utilized for the determination of the number of particles in extensive air showers; they were disposed directly above the block of ionization chambers, as well as at a distance of 30 meters from the center of the installation. The total number of hodoscopic counters was 144.

1. Electron-Photon Component of the Core of Extensive Air Showers

In order to verify the connection between* the energy of the electro-photon component of the core (E^{core}_{el-ph}) and the number of particles in the shower (N), we determined these quantities for every air shower, whose axis passed through the area covered by the ionization chambers**, and whose energy of the electron-photon component of the core exceeded 10^{11} eV.

** The cases of shower axis passing through the area covered by ionization chambers were chosen according to the characteristic distribution of ionization in the chambers of upper series.

* [Russians use the denotation [illegible]]

The spectrum of registered showers by the number of particles, of which the energy of the electron-photon component of the core exceeds 10^{11} eV, is plotted in Fig. 2. - Presented in the same Fig. 2 is also the spectrum of extensive atmosphere showers constructed according to data, available in literature for our observation altitude [1]. Comparison of these spectra shows that the form of the spectrum and the frequency of showers with a number of particles $> 2 \cdot 10^4$ coincide with [1]. Hence it follows that in each shower with a number of particles $> 2 \cdot 10^4$ the energy of the electron-photon component of the core (in a circle of 2 m radius) exceeds 10^{11} eV, which constitutes no less than 2 percent of the mean value of the total energy of the electron-photon of showers with a number of particles of $2 \cdot 10^4$ magnitude. The mean value of the energy of electron-photon component in cores of registered showers is substantially greater and for showers with a number of particles from $2 \cdot 10^4$ to $1 \cdot 10^6$ it constitutes 15 percent of the mean total energy of shower's electron-photon component. In some parts of showers the energy of the electron-photon component of the core exceeds the mean value of the total energy of the shower's electron-photon component. This points to the existence of great fluctuations in the development of showers observed at heights of mountains.

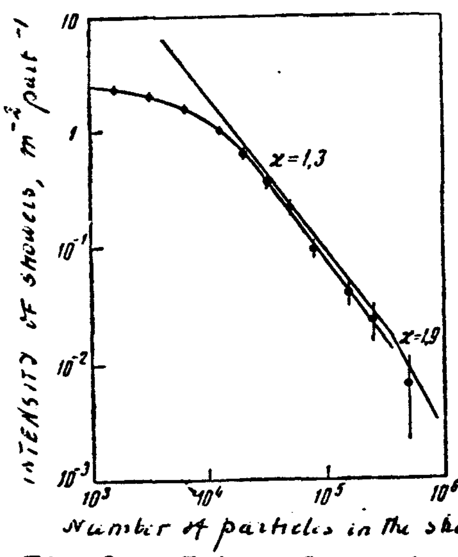

Fig. 2. - Integral spectrum of showers by the number of particles, of which the energy of the electron-component of the core is $> 10^{11}$ eV, (lower curve) and the integral spectrum of showers according to the number of particles after ref. [1] (upper curve).

In connection with this, comparison was conducted between our experimental data and the computations of ref. [3], into the basis of which a model of shower development, assuming large fluctuations on account of transfer in a single event of all the energy of a nucleon to one or several π^0-mesons, was postulated.

The experimental distribution of the value of $E_{el\,ph}^{core}/N$ in showers with particles numbering $10^4 - 10^5$, and also the computed distribution for electron-photon showers with particles numbering 10^4 and 10^5, are plotted in Fig. 3 (see ref. [3]).

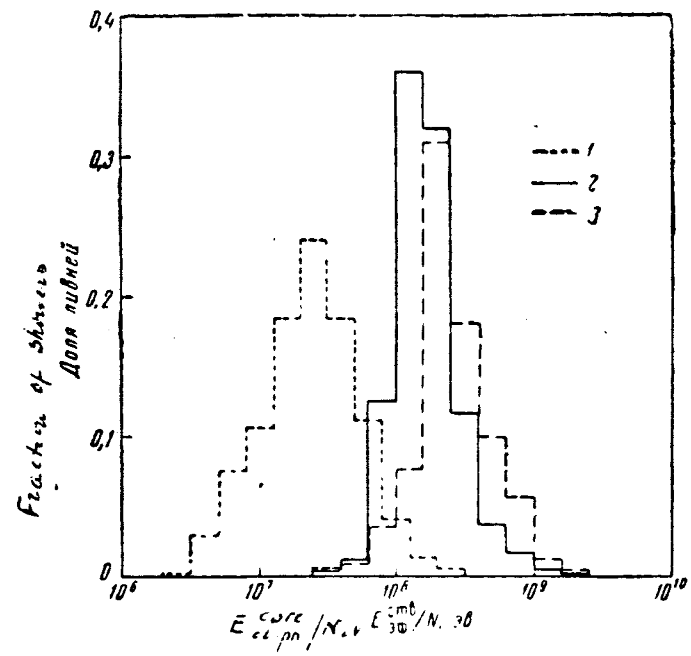

Fig. 3. - Distribution of showers according to the energy of the electron-photon component of the core $E_{el\,ph}^{core}/N$, corresponding to one electron of the shower: 1 — experimental data for $N = 10^4 - 10^5$; 2 — computed data [3] for $N = 10^4$; 3 — same for $N = 10^5$.

In the computation of ref. [3], the energy of electrons and photons with energy $> 10^9$ eV, moving near the axis of the shower, was taken for the value of E_{el-ph}^{core}. The distributions of E_{el-ph}^{core}/N have a similar form, but differ by their absolute values: the experimental values of E_{el-ph}^{core}/N are, as an average, substantially smaller than the computed. Such a discrepancy points unilaterally to the fact, that most of extensive showers could not be formed by primary protons by way of transfer of a substantial fraction of energy of the generating particle to one or several π^0-mesons.

* * *

2. Avalanches formed by Nuclear-Active Particles in the Substance of the Setup

In order to determine the energy spectrum of the nuclear-active particles by the ionization, observed in the lower series of our installation, it is necessary to convert the ionization bursts to the total number of electrons in the avalanche, passing through the cavity in Pb, and to link the number of electrons in the avalanche with the energy of the nuclear-active particle hitting the installation. The solution of the first problem, linked with the accounting of the angular distribution of electrons in the avalanche, is made more difficult by the fact, that in a series of cases two or more particles hit simultaneously the area of the installation. The transitional effects are absent on account of application of polyethylene chambers. The angular distribution of electrons in the avalanche was so chosen, that the best agreement be obtained between the relative values of ionization in the chambers situated at various distances from the axis of the avalanche. The cases, selected for analysis, by the data of hodoscopes had no accompaniment in the air, and that is why they could be viewed as cases of single hits of nuclear-active particles upon the installation. The angular distributions, utilized for the analysis, may approximately be characterized as follows. A direct particle flux emerges from one point of the upper Pb layer of the cavity and is divided into an isotropic part of a ($a = 1.0, 0.66, 0.50$ or 0.33 of the number of particles of direct flux) and into a part of electrons moving parallelwise to avalanche axis. The inverse flux was considered as isotropically emitted from the lower surface of Pb, proportionally to the direct flux of electrons, incident upon the corresponding part of that surface. The aggregate ionization from the inverse flux was assumed to be equal to the ionization of the direct flux [4]. The results of comparison of the calculation with the experiment are plotted in Fig. 4. Subsequently, we shall admit the angular distribution of particles, at which half of particles in the direct flux is distributed isotropically.

Resting upon the chosen angular distribution, one may link the total number of electrons in the electron-nuclear avalanche (N_{el-n})* with the aggregate ionization in the whole series of ionization chambers (I_Σ)

* [Subsequently, in formulas we shall keep the original Russian denotation for N_{el-n}, which is $N_{эя}$]

or with the ionization burst I_o in the chamber, through which passes the axis of the avalanche and which registers the greatest ionization in the given event. We may also link the frequency of ionization bursts $\nu_i(>I)$, observed in each of the separate chambers independently, with the number of avalanches, the axes of which hit one of the chambers of the series $\nu(>I_0)$. Without taking into account the simultaneous hitting of the installation by several nuclear-active particles, we obtain for the same events : $I_\Sigma / I_0 = 2{,}85$ and $\nu_i(>I) / \nu(>I_0) = 1{,}9$ for events in which $I = I_o$. In the experiment the respective quantities are equal to 3.3 and 2.15. Taking advantage of this difference we shall attempt to take into account the cases of nuclear-active particles hitting the installation by groups. Assume that a simultaneous appearance of two avalanches is observed, which differs from one another by m times; then,

$$\nu_i(>I) = 1{,}9\nu(>I_0)\,(1 + l\,/\,m^{\varkappa}),$$

where $\varkappa$ is the index of the integral spectrum of ionization bursts, and $I_\Sigma = 2{,}85 I_0 (1 + l\,/\,m)$. It is obtained experimentally that

$$\nu_i(>I)\,/\,\nu(>I_0) = 1{,}9\,(1 + l\,/\,m^{\varkappa}) = 2{,}15,$$
$$I_\Sigma\,/\,I_0 = 2{,}85\,(1 + l\,/\,m) = 3{,}3.$$

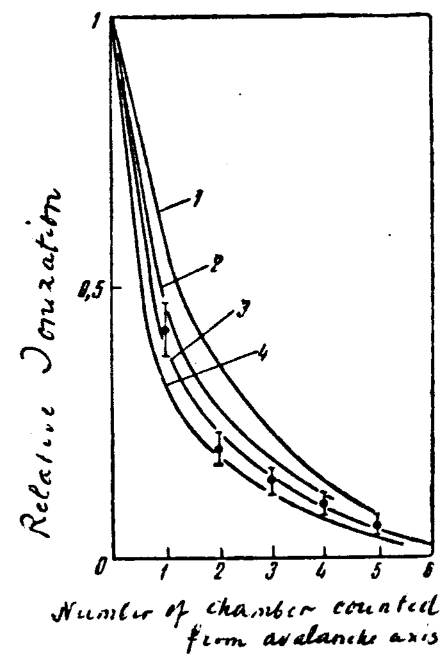

Fig. 4. - Distribution of ionization in polyethylene chambers disposed in a Pb cavity, at different share a of direct flux particles emerging from Pb as isotropically scattered (1 – a particles of direct flux moving along the axis of the avalanche) :

$1 - a = 1$; $2 - a = 0{,}66$; $3 - a = 0{,}50$; $4 - a = 0{,}33$

The solution of these equations gives l = 0.28 and m = 1.7. A direct calculation of the fraction of group bursts has led to the value $l = 0{,}29 \pm 0{,}02$. Finally, utilizing the selected angular distribution of electrons in the avalanche and the values found for l and m, we obtained the following correlations between the ionization bursts and the values of electron-photon avalanches in the Pb cavity of the installation :

$$N_{el-n} = 5.1 \cdot 10^5\, I_o\ ; \quad N_{el-n} = 1.54 \cdot 10^5\, I\ ; \quad I_{el-n} = 3.08 \cdot 10^5\, I\ .$$

We plotted in Fig. 5 the integral spectra of avalanches for the third and fourth series from separate nuclear-active particles, superposed with the aid of the above correlations. If we utilize the exponential form of approximation of spectra

$$\nu(> N_{эя}) = A\,(N_{эя}/10^4)^{-\varkappa},$$

we shall have for third series of chambers

$$A = 0{,}100 \pm 0{,}002,\quad \varkappa = 1{,}51 \pm 0{,}04 \quad at \quad 3\cdot10^3 < N_{эя} < 5\cdot10^4,$$
$$A = 0{,}3 \pm 0{,}04,\quad \varkappa = 2{,}2 \pm 0{,}2 \quad at \quad N_{эя} > 5\cdot10^4;$$

and for the fourth

$$A = 0{,}046 \pm 0{,}004,\quad \varkappa = 1{,}49 \pm 0{,}06 \quad at \quad 3\cdot10^3 < N_{эя} < 4\cdot10^4,$$
$$A = 0{,}12 \pm 0{,}04,\quad \varkappa = 2{,}2 \pm 0{,}2 \quad at \quad N_{эя} > 4\cdot10^4.$$

The variation of the integral spectrum of avalanches, caused by nuclear-active particles in the ionization interval corresponding to the passage of $(4 - 6)\cdot10^4$ relativistic particles, was already noted in certain works [2, 5, 6]. However, no unique opinion on this question has heretofore been asserted. In particular, the opinion was advanced in the work [7], that such a variation of the spectrum is absent. The results of the work [7] were compared with our data of Fig. 5, 6. For comparison, data of the work [7] were utilized, in particular those related to spectra by groups from three chambers in series which are located under the equivalent Pb layers. As may be seen in the Fig. 5 (next page), the data practically coincide. The index of spectrum inclination, determined with the help of an electronic computer by the same method as in the case of processing of our own data, was found to be equal to $\varkappa = 1.48 \pm 0.05$. The consolidation of our data with those of work [7] allows to make more precise the value of the index of the spectrum of ionization bursts after break: $\varkappa = 2.18 \pm 0.11$.

Aside from the total spectrum of avalanches, we constructed, according our data, the spectrum of avalanches $\nu_{од}$, not attended by the shower in air above the installation, registered by our apparatus. The minimum observed value of the shower constitutes 300 particles for a cascade parameter of the shower in the air, $s \leqslant 1.3$. Such cases, without accompaniment, may be interpreted as cases of primary protons passing through the atmosphere without interaction. The conversion from the ionization observed in separate chambers, or from aggregate ionization, to the number of particles in the avalanche passing through the third and the fourth series of chambers, is effected in this case without taking into account the cases of simultaneous hittings of the installation by two or more particles. The spectrum may be expressed in the form

$$\nu_{\text{од}}(> N_{\text{эя}}) = (2{,}7 \pm 0{,}5)\cdot 10^{-3}(N_{\text{эя}} / 10^4)^{-1{,}9 \pm 0{,}2}\ \text{part.}^{-1}\cdot \text{м}^{-2}$$

for the third series of chambers, and

$$\nu_{\text{од}}(> N_{\text{эя}}) = (4{,}3 \pm 0{,}4)\cdot 10^{-3}(N_{\text{эя}} / 10^4)^{-1{,}9 \pm 0{,}2}\ \text{part.}^{-1}\cdot \text{м}^{-2}$$

for the fourth series at $4\cdot 10^3 < N_{\text{эя}} < 4\cdot 10^4$.

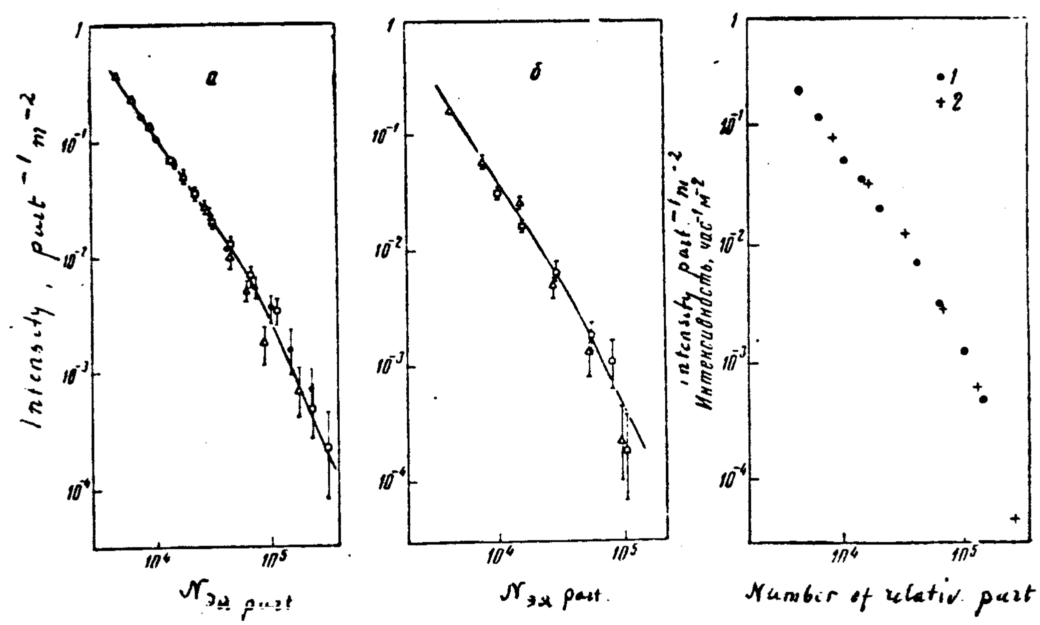

Fig. 5. - Integral spectra of avalanches, caused by separate nuclear-active particles in the third (a) and fourth (б) series of ionization chambers, obtained as a result of conversion: ● from maximum in the series of bursts I_0, △-from bursts in separate chambers I_i, □-from aggregate bursts by series, I_Σ: в-integral spectra of avalanches, caused by nuclear-active particles. 1 — with reference to [7]; 2 — with reference to [6].

* * *

3. Energy Spectrum of Nuclear-Active Particles

For the determination of the energy spectrum of nuclear-active particles by the spectrum of observed avalanches we utilized the method described in the work [8]. Assume, that the energy spectrum of nuclear-active particles has at the observation height an exponential character $Be^{-\gamma y}dy$, where $y = \ln(E/10^{12})$. The nuclear-active particle, hitting the absorber, forms in it an electron-nuclear avalanche. Assume that the mean number of particles in such an avalanche, $(N_{эя})$ at detector depth x being linked with the energy of the nuclear-active particle E by the correlation

$$\bar{N}_{эл}(E, x) = D(x)\,(E/10^{12})^{s(x)},$$

which takes in logarithmic coordinates the form

$$z_1 = \ln \bar{N}_{эл}(E, x) = \ln D + sy.$$

If the distribution of avalanches by $z = \ln N_{эл}$ at detector depth x is known from the nucelar-active particles of specific energy

$$y - W(z, y, x)\,dz = W(z - z_1, x)\,dz,$$

we may find the differential spectrum of avalanches at the same depth x from all the nuclear-active particles incident upon the detector:

$$\nu(z, x)\,dz = dz \int_{-\infty}^{+\infty} W(z - z_1, x)\,Be^{-\gamma y}\,dy =$$

$$= BD^{\gamma/s}\,e^{-\gamma z/s}\,M(x)\,dz/s,$$

where

$$M(x) = \int_{-\infty}^{+\infty} W(z - z_1, x)\,e^{-\gamma(z-z_1)/s}\,d(z - z_1)$$

is a constant value for the given x. The obtained integral spectrum

$$\nu(>N, x) = \frac{B}{\gamma} D^{\varkappa} M N_{эл}^{-\varkappa}$$

may be compared with the experimentally observed spectrum

$$\nu(>N, x) = A\,(N_{эл}/10^4)^{-\varkappa}$$

and the values B and γ, characterizing the energy spectrum of nuclear-active particles at the Pamir height can thus be found:

$$\frac{B}{\gamma} = D^{-\varkappa} M^{-1} A \cdot 10^{4\varkappa}, \quad \gamma = \varkappa s.$$

The values of D, s and M depend upon the assumptions, at which the avalanche spectrum is computed from the nuclear-active particle of the given energy $W(z, y, x)\,dz$.

The calculation of $W(z, y, x)\,dz$ is conducted by Monte-Carlo method in several variants.

In the first variant it was assumed that :

1) the fraction of energy, preserved by the nucleon at interaction with the carbon nucleus is equal to $\alpha_C = 0.7$, and with the Pb nucleus — $\alpha_{Pb} = 0$;

2) at interaction of secondary $\pi^{\pm}$-mesons with the Pb and C nuclei, the nonelasticity factor is equal to 1;

3) a third of energy, transferred to mesons, is carried away by π^0-mesons, which create the spectrum of photons dE/E^2 in the energy interval $E_{min} < E < E_{\pi^0}$, where E_{π^0} is the aggregate energy of all the π^0- mesons of a single event.

The second variant differed from the first only by the fact, that the fraction of energy, preserved by the nucleon at interaction with the Pb nucleus was taken equal to 0.5 and not zero. In the third variant it was additionally assumed that in 30 percent of nucleon interaction events, determined by the method of random tests, all the energy of the π^0- component is carried by a single photon.

The locations of nuclear interactions of incident nucleons were found by the Monte-Carlo method. From every interaction event there emerged an electron-nuclear avalanche, which was developed in the detector and partially reached the third and the fourth series of ionization chambers. For simplicity and practical purposes we considered separately each avalanche from by the decay of π^0-mesons of the same event, which were computed by the method of consecutive generations.

If the interaction took place in the graphite, the aggregate number of radiation units was taken into account from the place of interaction to the levels of the third or fourth series of ionization chambers. For the calculation of avalanches from $\pi^{\pm}$-mesons we utilized the cascade curves of the work [9] for the spectrum of photons or of a single photon, depending upon the character of the event. To take into account the avalanches from π^0 - mesons, we constructed the nuclear-cascade curve for graphite, from which we found the fraction of energy transferred by the charged mesons to the electron-photon avalanche from the place of their formation to the level of observations; then, the magnitude of the avalanche, at the depth required by us, was determined from the curve of the photon spectrum of [9].

The computation of avalanches, generated in the upper Pb, differs from the others only by the accounting of the transitional effect Pb - graphite.

All the avalanches, linked with one and the same primary particle, were summed up among themselves at the depth of the third and fourth series of ionization chambers. Then, for every primary energy we constructed the distribution of avalanches by the value of W (z, y, x) and found the values of $\bar{N}_{эп}$, D and s (Table 1).

TABLE 1

	1st variant		2nd variant		3rd variant	
	3rd series	4th series	3rd series	4th series	3rd series	4th series
$N_{эп}$, $E = 10^{11}$ эв	136	80	163	83	170	87
$N_{эп}$, $E = 10^{12}$ эв	1410	870	1620	930	1520	1050
$N_{эп}$, $E = 10^{13}$ эв	14800	9300	16200	10450	13200	12300
D	$1{,}41\cdot10^3$	$8{,}7\cdot10^2$	$1{,}62\cdot10^3$	$9{,}3\cdot10^2$	$1{,}52\cdot10^3$	$1{,}05\cdot10^3$
s	1,01	1,04	1,00	1,05	0,95	1,08

In Table 2 we compiled the values of M (x), computed for different variants, and the values of γ and B/γ, obtained by way of comparison of the computed spectra of avalanches for the third and fourth series of ionization chambers with the observed ones.

TABLE 2

same captions as in Table 1

$E<3\cdot10^{13}$ эв	$M(x)$	1,16	1,49	1,07	1,11	1,063	1,121
	γ	$1{,}53\pm0{,}04$	$1{,}51\pm0{,}1$	$1{,}51\pm0{,}04$	$1{,}56\pm0{,}1$	$1{,}44\pm0{,}04$	$1{,}61\pm0{,}1$
	B/γ	$1{,}66\pm0{,}03$	$1{,}17\pm0{,}10$	$1{,}46\pm0{,}03$	$1{,}43\pm0{,}12$	$1{,}62\pm0{,}03$	$1{,}18\pm0{,}10$
$E>3\cdot10^{13}$ эв	$M(x)$	1,545	3,24	1,19	1,42	1,205	1,75
	γ	$2{,}2\pm0{,}2$	$2{,}3\pm0{,}2$	$2{,}2\pm0{,}2$	$2{,}3\pm0{,}2$	$2{,}1\pm0{,}2$	$2{,}4\pm0{,}02$
	B/γ	14 ± 2	8 ± 3	14 ± 2	16 ± 5	16 ± 2	10 ± 3

Comparing the different variants of the calculation one may notice that for variants 1 and 3, the energy spectra, obtained from the spectra of bursts in the third and fourth series, do not coincide with one another. Only the variant 2, in which the absence of energetically liberated π^0 - meson is assumed, and the nonelasticity factor in Pb, equal to 0.5, provide identical values for γ and B/γ by the third and fourth series. Accordingly, the energy spectrum of nuclear-active particles at Pamir height may be represented in the form

$$f(>E) = (1{,}46 \pm 0{,}03)\,(E\,/\,10^{12})^{-1{,}51 \pm 0{,}04}\ \text{part}^{-1}\text{м}^{-2} \quad \text{for}\ E < 3\cdot 10^{13}\ \text{eV},$$
$$f(>E) = (14 \pm 2)\,(E\,/\,10^{12})^{-2{,}2 \pm 0{,}2}\ \text{part}^{-1}\text{м}^{-2} \quad \text{for}\ E > 3\cdot 10^{13}\ \text{eV}$$

Analogously the integral energy spectrum of nuclear-active particles, moving either without attendance by shower in the air or with nonregistered attendance ($N < 300$), can be obtained :

$$f_{\text{од}}(>E) = (0{,}136 \pm 0{,}017)\,(E\,/\,10^{12})^{-1{,}9 \pm 0{,}2}$$

$$\text{for } 2.5\cdot 10^{12}\ \text{eV} < E < 2.5\cdot 10^{13}\ \text{eV}.$$

Although the observed magnitude of the avalanche in the lower series of ionization chambers can be induced by nuclear-active particles of various energy, it may be eventually useful to utilize for the qualitative analysis the approximate relationship between the magnitude of incident particle energy and the number of electrons in the avalanche. In the interval, of interest to us, we have for the third series

$$E = (5{,}9 \pm 0{,}1)\,(N_{\text{эл}}\,/\,10^4)\cdot 10^{12}\ \text{eV}$$

and for the fourth

$$E = (10 \pm 0{,}9)\,(N_{\text{эл}}\,/\,10^4)^{0{,}95}\cdot 10^{12}\ \text{eV}$$

It may be seen that in these correlations the relationship factors are below average, following from Table 1. This distinction is explained by the influence of the form of the energy spectrum of the observed nuclear-active particles and by the fluctuations between the magnitude of the avalanche in Pb and the energy of the nuclear-active particle.

* * *

4. Interaction and Absorption Mean free Paths of Nucleons in the Atmosphere.

Data on the intensity of the flux of nuclear-active particles at the depth of 640 g/cm^2 may be compared with the intensity of nucleons at atmosphere boundary and in this way the absorption of nucleons in the atmosphere can be determined. If $F(>E_0, 0)$ particles with energy $> E_0$ are incident at atmosphere boundary per unit of solid angle, the global number of such particles at observation level will constitute

$$F(> E_0, x) = \int_0^{\pi/2} 2\pi F(> E_0, 0) \exp\left(-\frac{x}{\lambda_n \cos\theta}\right) \sin\theta \, d\theta =$$

$$= 2\pi F(> E_0, 0) \exp(-x / \lambda_n) \,/\, (1 + x / \lambda_n),$$

where λ_n is the absorption path of nucleons in the atmosphere. Hence it follows

$$\lambda_n = x / \ln\left[2\pi F(> E_0, 0) \,/\, F(> E_0, x)\,(1 + x / \lambda_n)\right].$$

The number of nucleons at atmosphere boundary is determined by the energy spectrum of the primary cosmic radiation [10] with the accounting of the relative fraction of nuclei with a different charge in the primary radiation [11]:

$$F(> 10^{12}\ \mathrm{eV}, 0) = (314 \pm 66)\ \mathrm{part}^{-1}\ \mathrm{m}^{-2}\ \mathrm{sterad}^{-1}$$
$$F(> 10^{13}\ \mathrm{eV}, 0) = (7.5 \pm 1.6)\ \mathrm{part}^{-1}\ \mathrm{m}^{-2}\ \mathrm{sterad}^{-1}.$$

Utilizing these values and the above energy spectrum of nuclear-active particles at the —— 640 g/cm^2 depth, we shall obtain the values of the path for absorption :

$$\lambda_n(> 10^{12}\mathrm{eV}) = 120 \pm 5\ \mathrm{g/cm^2}, \quad \lambda_n(> 10^{13}\mathrm{eV}) = 124\ \mathrm{g/cm^2}.$$

In the above estimates it was silently assumed, that all the nuclear-active particles at mountain heights are nucleons. Such an assumption is apparently not justified. However, if we consider even that π^0- mesons constitute 30% of the total flux of nuclear-active particles at mountain height [12], the value of nucleon absorption paths varies little :

$$\lambda_n(> 10^{12}\mathrm{eV}) = 115\ \mathrm{g/cm^2}, \quad \lambda_n(> 10^{13}\mathrm{eV}) \doteq 119\ \mathrm{g/cm^2}.$$

The free path for the nuclear interaction is determined on the basis of registration of nuclear-active particles moving without their being attended by an air shower. The absence of accompaniment may be considered as evidence that the given particle passed the atmosphere without a single interaction. Such particles can be only primary protons , for α-particles and heavier nuclei would inescapably be attended by an air shower. Assume that there are $F_p(>E_0, 0)$ protons at atmosphere boundary. The number of protons without shower accompaniment at depth x will be

$$F_p(>E_0, x) = 2\pi F_p(>E_0, 0)\exp(-x/\lambda)/(1+x/\lambda),$$

where λ is interaction path of nucleons in the atmosphere. Hence it follows that the relative number of particles without attendance will be

$$\frac{F_p(>E_0, x)}{F(>E_0, x)} = \frac{F_p(>E_0, 0)}{F(>E_0, 0)}\exp\left[-x\left(\frac{1}{\lambda}-\frac{1}{\lambda_n}\right)\right]\left(1+\frac{x}{\lambda_n}\right)\Big/\left(1+\frac{x}{\lambda}\right).$$

The path for interaction can be expressed in the form

$$\frac{1}{\lambda} = \frac{1}{\lambda_n} + \frac{1}{x}\left[\ln\frac{F_p(>E_0, 0)F(>E_0, x)}{F(>E_0, 0)F_p(>E_0, x)} + \ln\frac{(1+x/\lambda_n)}{(1+x/\lambda)}\right]$$

Substituting the corresponding values, we shall obtain

$$\lambda \leqslant 90 \pm 5\ \mathrm{g/cm^2} \quad \text{for} \quad E \geqslant 10^{12}\ \mathrm{eV}$$
$$\lambda \leqslant 83 \pm 5\ \mathrm{g/cm^2} \quad \text{for} \quad E \geqslant 10^{13}\ \mathrm{eV}$$

The obtained values of the interaction path for protons in the atmosphere constitute the upper limit for the minimum registered loss of energy by a particle in the atmosphere constitutes $\sim 5 \cdot 10^{11}$ eV.

* * *

5. Relationship between the Energy of a Nuclear-Active Particle and the Value of the Attending Shower

The apparatus utilized by us allowed to measure simultaneously the energy of nuclear-active particles, the number of particles in an extensive air shower and the energy of the electron-photon component of the showers' core. The correlation between these quantities fluctuate strongly from case to case. Presented in Fig. 6 are the integral distributions : a) of the number of particles in an extensive air shower at the energy of the electron-photon component of shower's core from $3.5 \cdot 10^{11}$

to $5.6 \cdot 10^{11}$ eV, b) of the energy of the electron-photon component of the shower's core at energy of the nuclear-active component of the core from $4.2 \cdot 10^{12}$ to $8.4 \cdot 10^{12}$ eV, c) of the energy of the nuclear-active component of the core at total number of particles in the shower from $5 \cdot 10^5$ to $1 \cdot 10^6$ and d) with energy of the electron-photon component of the core in the interval $(1.8 - 3.6) \cdot 10^{12}$ eV.

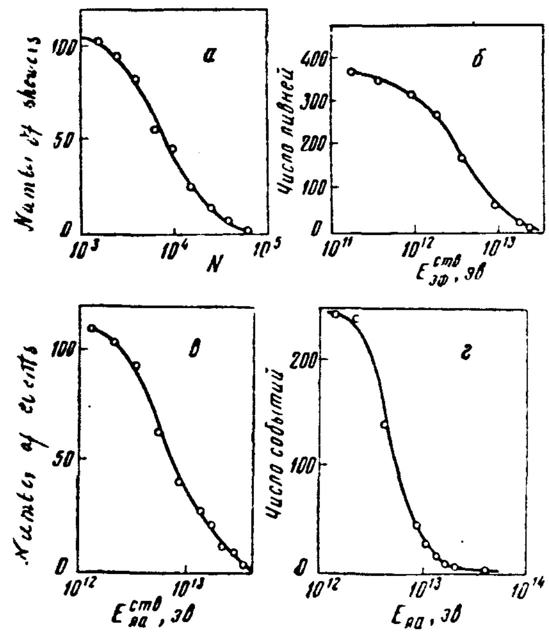

Fig. 6

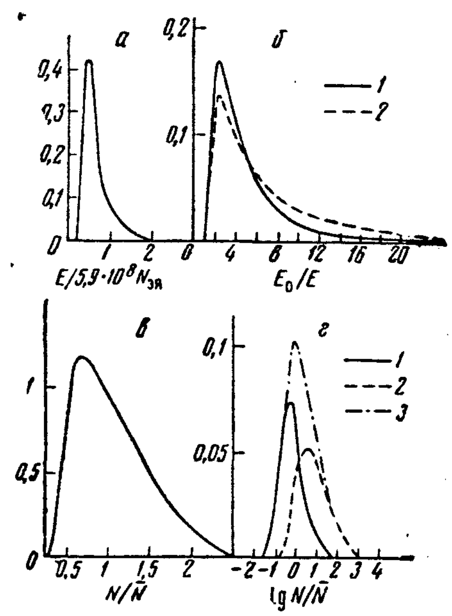

Fig. 7

Fig. 6. a — Integral distribution of showers by the number of particles at energy of the el-ph component of the core = $(3.5 - 5.6) \cdot 10^{11}$ eV ; δ - integral distribution of showers by the energy of the el-ph component of the core at energy of the nuclear-active particle = $(4.2 - 8.4) \cdot 10^{12}$ eV ; в — integral energy distribution of nuclear-active particles in showers with a number of particles $N = 5 \cdot 105 - 10 \cdot 10^5$; г — integral energy distribution of nuclear-active particles at $E^{core}_{el\text{-}ph} = (1\text{-}8 - 3.6) \cdot 10^{12}$ eV.

Fig. 7. a — energy distribution of nuclear-active particles, generating at the level of the 3rd series of ionization chambers an avalanche with $N_{эа}$ particles (second variant of calculation); δ - energy dustribution of primary nucleons arriving at the Pamir level with energy in the interval E — 2E : 1 — constant fraction of preserved energy, $\alpha = 0.5$; 2 — fluctuating fraction of preserved energy, $\bar{\alpha} = 0.5$; в — distribution of showers, generated by primary protons with energy 10^{14} eV, by the number of particles at Pamir level [13]; г - distribution of showers attending at Pamir level a nucleon with energy E — 2E : 1 — showers from primary protons, 2 — showers from primary nuclei, 3 — showers from primary protons and nuclei. - The relative number of showers is plotted in ordinates.

For the quantitative analysis we selected the fluctuations of the total number of particles in an extensive air shower for a given value of the ionization induced in the lower series of ionization chambers by the high-energy nuclear-active particles. The observed fluctuations are the result of combinations of probable interconnections : between the observed ionization and the energy of the particle having hit the detector of nuclear-active particles, fluctuations in the value of the energy of primary nucleon at atmosphere boundary, giving a nuclear-active particle of pre-assigned energy at observation level, fluctuations of the number of particles in an extensive air shower for a given energy of the nuc eon at atmosphere boundary on account of fluctuations in the development of the shower and also because the packing of a part of primary nucleons into α -particles and heavier nuclei. The essential assumption of the computations completed by us consists in the admission of statistical independence of the above-enumerated fluctuations. The enumerated distributions are plotted in Fig. 7. The calculation of the interconnection between the observed ionization and the energy of the nuclear-active particle (Fig. 7.a) has been discussed at length in the preceding section. The distribution of showers by the total number of particles from the given-energy nucleon was borrowed from the work [13] (Fig. 7, δ). In these calculations the distributions of the number and the place of interaction of the "leading" nucleon in the atmosphere are taken into account. It is assumed that avalanches from π -mesons have a relatively short path on account of uniform distribution of energy, lost by the nucleon between the secondary π - mesons. The composition of the primary cosmic radiation was taken in correspondence with the experimental data of [11] in the region of energies $E_o < 10^{12}$ eV (Table 3).

TABLE 3

	p	α	M	H	VH
	1	4	14	31	51
Relative number of particles of given energy (in%) per nucleon	86	13	0.88	0.33	0.12
Relative number of nucleons (in %) with ident.energy from diff.groups	52	31	7.5	6.1	3.7

During the calculation of showers from nuclei it was estimated that one of the nucleons of the nucleus, with atomic weight A is registered in the detector of nuclear-active particles. As to the shower, it is created by all the A-nucleons, while the fluctuations in the development of such a shower is $A^{1/2}$ times smaller than in a shower from a single nucleon of corresponding energy. The energy distribution of primary nucleons (fig. 7, 6), giving at observation level a nucleon with energy E, is determined by the expression

$$W(E_0, E)\,dE_0 = \frac{W(E, E_0)\,f(E_0)\,dE_0}{\int\limits_E^\infty W(E, E_0)\,f(E_0)\,dE_0}.$$

Here

$$f(E_0)\,dE_0 = BE_0^{-(\gamma+1)}dE_0$$

is the energy spectrum of the primary nucleons

$$W(E, E_0) = e^{-t}\frac{t^i}{i!}$$

is the probability that the primary nucleon of energy E_0 creates at depth t nuclear paths of nucleons with energy $E = \alpha^i E_0$ with a fraction α of energy preserved in the interaction. The calculation was completed at different assumptions as regards the quantities α, γ and the length of the free path for the nuclear interaction.

Comparison of experimental data with the computed combined effect of the enumerated causes of fluctuations of the correlation between the energy of the observed nuclear-active particle and the magnitude of the extensive air shower is made in Fig. 8. For nuclear-active particles with energy $(1.3 - 2.6) \cdot 10^{12}$ eV the calculation agrees well with experiment. For nuclear-active particles of great energy there exists an obvious discrepancy between the calculation and the experiment. This result does not depend on whether a constant value $\alpha = 0.5$ is taken for the fraction of conserved energy, or it is estimated that α may have two values : $\alpha = 0.2$ and $\alpha = 0.8$ at $\tilde{\alpha} = 0.5$. We analyzed different assumed causes of discrepancy between the calculation and the data of the experiment.

The variation of spectrum index of primary cosmic radiation γ in the energy region $E_0 \cong 10^{15}$ eV cannot be manifest in our experiments. We assumed that the spectrum index of primary nucleons γ varies from $\gamma = 1.5$

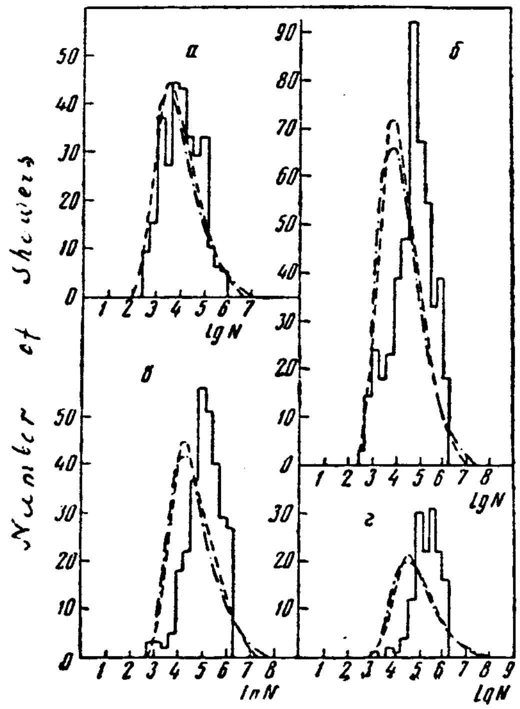

Fig. 8

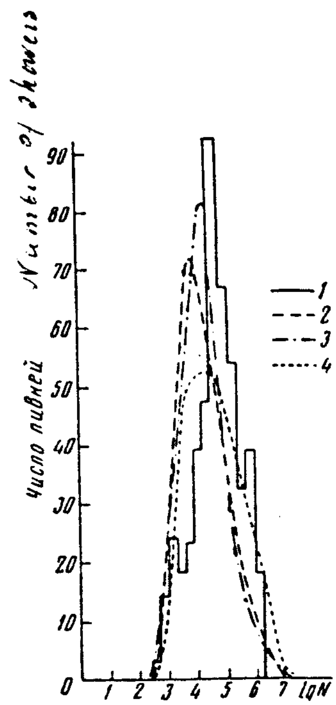

Fig. 9

Fig. 8. Distribution of showers, accompanying at Pamir height a nuclear-active particle with energy E, by the number of particles : a — $E = (1.3 - 2.6) \cdot 10^{12}$ eV, б — $E = (2.6 - 5.2)\ 10^{12}$ eV в — $E = (5.2 - 10.4) \cdot 10^{12}$ eV, г — $E = (1.04 - 2.08)\ 10^{13}$ eV ; Histogram : experimental data, dashes — calculation for a constant fraction of conserved energy $\alpha = 0.5$; stroke-dashes — computation for a fluctuating fraction of conserved energy, $\bar{\alpha} = 0.5$.

Fig. 9. - Distribution of showers attending nuclear-active particles with energy $(2.6 - 5.2) \cdot 10^{12}$ eV at Pamir level, by number of particles : 1 — experimental data, 2 — computation at constant fraction of conserved energy, dependent upon the energy of the nucleon E (in 2 and 3 — all the nuclear-active particles at Pamir level are nucleons) 4 — calculation at constant fraction of conserved energy, $\alpha = 0.5$ (70% of nuclear-active particles at Pamir level are nucleons and 30 percent are μ -mesons.

to $\gamma = 2.0$ at energy $E_o = 3 \cdot 10^{13}$ eV, that is, at such energy, at which a variation is observed in the spectrum of nuclear-active particles at mountain heights. However, calculation has shown that such an assumption increases still further the discrepancy between the experiment and the calculation. Subsequently, the contribution of $\pi^{\pm}$ - mesons to the flux of nuclear-active particles observed at mountain level was taken into account, and it was tested how the character variation of an elementary event can influence, namely that in connection with analysis of the data on extensive air showers considered earlier. When computing the interrelation between the energy of the $^{\pm}$-meson observed at mountain level with the energy of the primary nucleon at atmosphere boundary, only $\pi^{\pm}$-mesons formed by nucleons were taken into account. At the same time it was estimated that the contribution of the $\pi^{\pm}$-mesons generated by $\pi^{\pm}$ -mesons could be neglected. The spectrum of π -mesons, generated in an elementary event, was taken in the form dE/E^2 within the interval from E_{min} to E_{max}. The value of E_{max} was estimated equal to $(1 - \alpha) E_{nucl}$, and E_{min} was determined from the normalization of the above spectrum to total energy, transferred by π - mesons, and of the total number of π-mesons in the acts or events observed in photoemulsion at corresponding energies. The pattern of elementary event variation at $3 \cdot 10^{13}$ eV was taken in the following form: for energy $< 3 \cdot 10^{13}$ eV the fraction of conserved energy is $\alpha = 0.5$; the nucleons with energy above $3 \cdot 10^{13}$ eV conserve the fourth part of energy ($\alpha = 0.25$), and at the same time the fourth part of energy goes to the formation of π -mesons and half of the energy is transferred to a single γ-quantum. It may be seen in Fig. 9 that both, the accounting of $^{\pm}$-mesons and the variation of the pattern of the elementary event, imrove the agreement of the calculation with the experiment.

* * *

CONCLUSION

The interactions of nucleons with nuclei are best of all investigated in accelerators and in the region of energy adjacent to accelerating. The generally admitted energy pattern of the elementary event can be described as follows : the incident nucleon conserves at collision with a light nucleus nearly half of its energy, as an average; the energy spectrum of particles forming in the collision is, as a whole, quite hard: thus, particles are encountered, the energy of which is of the same order as that of the incident particle. The above-described experimental data fit well such a scheme of nucleon interaction with nitrogen and oxygen nuclei when the energy of the incident nucleons is less than $(1 \div 3) \cdot 10^{13}$ eV. The effective cross section for the nonelastic collision corresponding to the observed free path at 10^{12} eV in the air $\lambda = 90$ g/cm^2, does not differ from the value of the cross section obtained for an energy $\sim 10^{10}$ eV on the accelerator. Up to what energies of the incident nucleon are such characteristics of the elementary event preserved ? The theory of complex orbital moments forecasts the increase of the effective cross section for the nonelastic interaction of nucleons with nuclei at transition from energies of 10^{10} eV to 10^{15} eV. The decrease of the free path of primary nucleons with energy near 10^{13} eV , obtained in our measurements, does not emerge beyond the limits of statistical errors when compared with nucleons of lower energies. The experimental indications on the variation in the elementary event were obtained during studies of extensive air showers and at measurements of the energy spectrum of γ-quanta in the upper part of the atmosphere with the aid of photoemulsions. The data on extensive air showers pointed to the necessity of changing the characteristics of the elementary event in the energy interval of primary particles, $10^{14} - 10^{15}$ eV [14]. The variation of the energy spectrum of γ-quanta in the upper part of the atmosphere was observed for energy $\sim 10^{12}$ eV [15]. This corresponds to energy of primary nucleons $E_0 > 10^{13}$ eV. However, these estimates of the energy of primary particles, at which some peculiarities are observed, do not contradict one another, for at formation of extensive air showers primary nuclei play a great role: for them the energy $E_0 > 10^{14}$ eV corresponds the energy $\sim 10^{13}$ eV on a single nucleon of the nucleus. The analysis of the distribution of extensive air showers by the total number of particles, described in the present work, when these showers are accompanying nuclear-active particles of given energy for the energy region

$E > 3 \cdot 10^{12}$ eV, leads to the assumption of the change in the pattern of the nucleon collision event with nuclei of air atoms at incident nucleon energy $E_0 > 10^{13}$ eV. The character of such a change is the same as the one that allowed to explain the peculiarities of the energy spectrum of γ-quanta in the upper atmosphere [16] and the data on extensive air showers with a number of particles $10^4 - 10^6$ [14]. This change of the event must lead to the increase of energy transfer to the electron-photon component, to a greater fractionation of energy of the primary nucleon between secondary particles.

An alternate explanation of our data on the spectrum of extensive air showers, attending nuclear-active particles of given energy at mountain level, could be sought in the assumption of sharp variation in the composition of primary cosmic radiation at $E_0 \cong 10^{13}$ eV toward significant prevailing of primary nuclei and a nearly total absence of protons. However, comparison of data on the fluctuations of the Čerenkov radiation and of the number of μ-mesons in extensive air showers with the results of the study of the composition of primary cosmic radiation by means of balloons and rockets points to the constancy of the composition in a broad interval of energies from 10^{10} to 10^{16} eV [10].

**** THE END ****

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